ACTA MONTANA 1992
Series A, No. 2(88), 179-192

SEISMICITY ASSOCIATED WITH DEEP-LEVEL MINING

W A Lenhardt

Department of Geophysics, Central Institute for Meteorology and Geodynamics,
Hohe Warte 38, A-1190 Vienna, Austria

Abstract: During the past five years, several research projects on the causes of mining-induced seismicity have been carried out by the Rockburst Research Department at Western Deep Levels Limited. This paper summarizes the results of these investigations. Several types of mining-induced seismic events are addressed and models of their mechanisms are presented. It is shown that most of the seismicity results from mining in geologically disturbed areas, and ways and means are discussed to reduce the seismic potential. Stabilizing pillars, for instance, have been introduced to reduce stresses at the stope face and to alleviate the face-bursting problem. However, facebursts still occur in areas of very low stresses, and pillars became the source of very large seismic events (M>3). At this stage, the understanding gained of pillar associated events allows a review of current mining practices. Further, it permits to judge the efficiency of different measures to alleviate the effects due to various seismically prone situations which might be encountered.

Key words: mining-induced seismicity, types of rockbursts, mechanisms.

1. INTRODUCTION

The results presented in this paper are mainly based on the article "Seismicity associated with deep-level mining at Western Deep Levels Limited" (Lenhardt, 1992). However, the paragraph on mine-dump events has been added, since the frame of the "International Symposium on Mining-Induced Seismicity" held in Liblice 1992 included reservoir-induced seismic events.

The gold mine Western Deep Levels Limited ('WDL') is situated approximately 70 km to the west of Johannesburg (South Africa). The mine extracts two gold bearing reefs, the Ventersdorp Contact reef (between 1500 and 2500 m below surface) and the Carbon Leader reef (between 2300 and 3500 m below surface). Both reefs are inclined by about 20 degrees and are nearly parallel. Mining operations are carried out with the use of three shafts. The rockmass can be described as 'hard-rock', since the uniaxial-compressive strength (UCS) of the Witwatersrand quartzite exceeds 200 MPa and the Youngs's modulus amounts to approximately 70 GPa.

Seismicity is experienced as the major obstacle during mining operations at WDL. Approximately 700 seismic events (M>0), 80 per cent of which were located on the mine itself, are recorded by the mine's seismic network per month. The remaining 20 per cent are spread between the neighbouring mines of WDL. As mining operations extend laterally and advance deeper, aspects of mining related seismicity did, and still do, attract interest. A number of papers describing detailed observations, and research efforts and results have been published (Ortlepp, 1984, McGarr, 1984, Spottiswoode, 1989). This paper builds on this expertise and presents some results which will hopefully contribute towards safer mining operations.

2. DISTRIBUTION OF SEISMIC EVENTS

2.1. Trends

Generalizations are always a great help when a wide area of problems is addressed, even if the phenomena of rockbursts is regarded as a already very specific one. Although general trends are less informative, they allow to split a certain domain of interest into categories thus clarifying different causes.

As seismicity levels are high in deep level mining, a reasonable amount of data could be gathered and evaluated. The following paragraphs try to highlight some issues which are likely to be raised in many discussions regarding this issue.

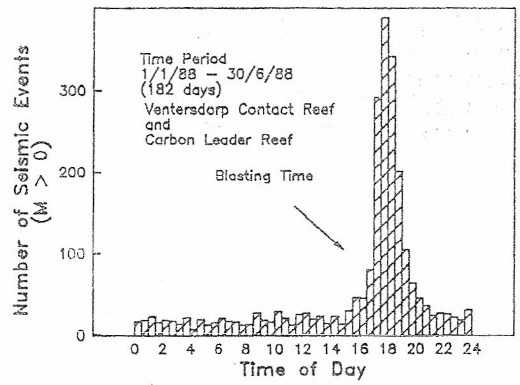

Fig.1 Diurnal distribution of mining-induced seismicity.

2.1.1. Time

Most mining-induced seismic events are observed within four hours after the blast (Fig.1, Lenhardt, 1989a). The rest of the seismicity is spread evenly over the remaining period of 20 hours. This observation does not allow any further conclusions. The magnitude distributions during these two time spans show a remarkably different slope, however. Larger events (M>2) occur more often four hours after the blast than shortly after the blast whereas most small events (0<M<1) are triggered during blasting operations or are released shortly thereafter.

An average weekday distribution demonstrates the time dependence again (Fig.2, Lenhardt, 1992): All events (M>0) are evenly spread throughout the week. Similar seismicity levels are experienced from Mondays to Fridays. On average, Saturdays experience approximately half the seismicity of a normal weekday since production carries on only every second Saturday. The lowest seismic activity is experienced on Sundays when no blasting operations are normally carried out.

More light can be shed on the problem from an examination of the distribution of larger events (M>2) during the week. Now, a slight increase between Mondays and Fridays becomes apparent (Fig.3, Lenhardt, 1992).

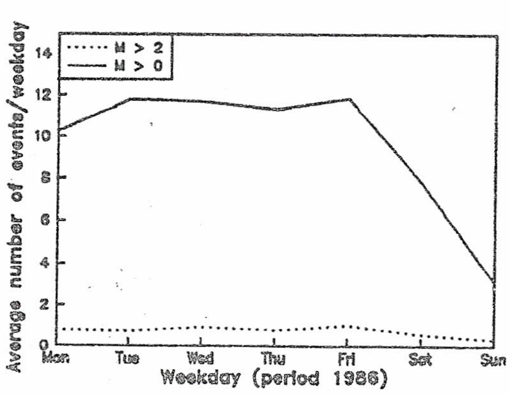

Fig.2 Weekday distribution of seismic activity (M>0).

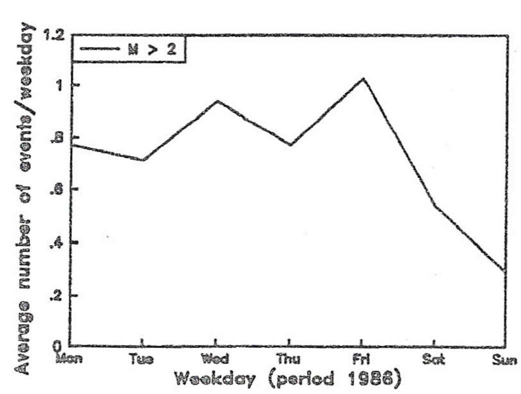

Fig.3 Weekday distribution of larger events (M>2).

Annual distributions (Fig.4, Lenhardt, 1992) show no time dependence of the seismic activity, either for small or for large events.

Data from the previous five years (1986 - 1990) support the time dependence on a small scale: When the two mining horizons, VCR and CLR, were separated and only larger events (M>3) were considered, the following observation was made: most (70 per cent) of large events occurred on the VCR four hours after the blast - contrary to large events on the CLR which tend to occur mainly (70 per cent) within four hours of the blast. Hence, as one would expect, inelastic processes, which also result in an excessive amount of closure, take place faster at greater depth (CLR) than at intermediate depth (VCR). The process which leads to the final occurrence of larger events is governed by the time dependent behaviour of the rock mass surrounding underground excavations. The time-dependent deformation of the rockmass should therefore gain more attention when modelling exercises are conducted.

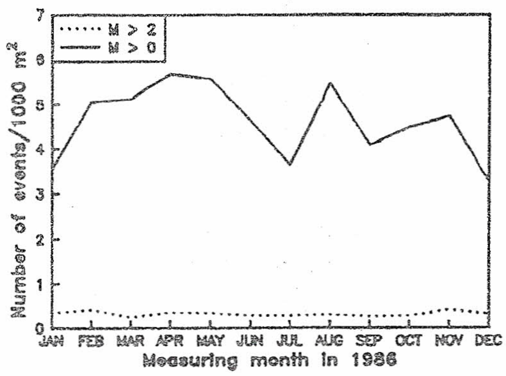

Fig.4 Annual distribution of seismicity.

A more detailed study (Piterek & Lenhardt, 1990) on blasting versus non-blasting related seismicity, which tried to exclude effects brought about by dykes and faults, confirmed the time dependence.

2.1.2. Space

Most seismic events occur in the ultimate vicinity of the reef horizon (50 m from the reef, see Fig. 5, Lenhardt, 1988). It was noticed that larger events M>3 show a tendency to occur rather in the footwall than in the hangingwall. Factors that contribute to this asymmetry are not systematic mislocations (most events M>1 locate around the reef horizon), owing to the existence of pillar foundation and abutment failures. But some large events were also observed on WDL which originated very deep or abnormally shallow. So far, the deepest large event (M>3) located in the shaft pillar - 400 metres below the projected level of mining (Lenhardt, 1988). Obviously, the point where the event originated fell into the zone where stress changes due to the surrounding mining excavations were substantial. Nevertheless, few other exceptions were noticed. They are :

1) Events along abutments (sidewalls of longwalls)

2) Mine-dump events.

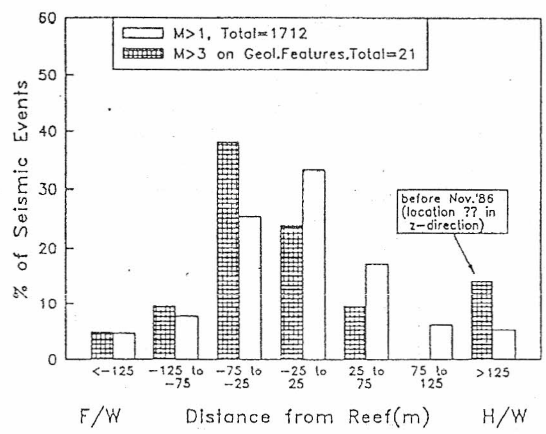

Fig.5 Seismic events and their distance from the reef.
(F/W = footwall, H/W = hangingwall)

2.1.3. Production

The correlation of production with seismicity is only meaningful if a large range of data can be evaluated. Figure 6 (Lenhardt, 1992) shows the correlation between these two data-sets for M > 0 from the Carbon Leader reef. The correlation suggests a linear relationship between production and the number of events (M>0) during the same time intervals. This fact is not surprising since the amount of mining represents the amount of stress change which ultimately leads towards instability. The slope in Fig.6 (events versus centares) is often used in the industry to express seismicity levels while taking the dependence of seismicity on the amount of production into account.

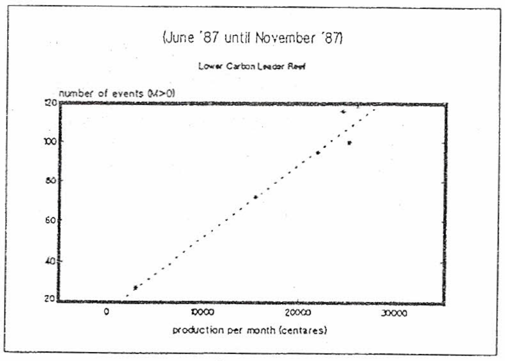

Fig.6 Seismicity (M>0) versus production.

Larger events (M>2) do not correlate with production - no relationship exists any more. Other factors than 'centares mined' or 'volume extracted' determine the stability of underground workings: rock properties, geological features and mining geometry.

3. OBSERVATIONS

3.1. Shear slip events

It is common knowledge that most of the very large seismic events (M>3) in the vicinity of mine workings occur along geological features - 62 per cent on WDL (Fig.7, Lenhardt, 1988). This fact is reflected also in the seismic behaviour of the four major gold-mining districts in South Africa. Not only do they experience dissimilar levels of seismicity but also their individual maximum expected magnitude differs (Mendecki et al., 1990). Assuming that the magnitude of an event is directly related to the seismic moment (Hanks & Kanamori, 1979), which itself describes the extent of the rupture area, mining regions with faults of large throws (>100 metres) are expected to release much larger seismic events than other regions where faults are not regarded as an obstacle for mine planning and longwall mining can be carried out. It should be noted, however, that no stringent relationship between the seismic moment and the magnitude exists - otherwise the stress drop would be identical for all seismic events.

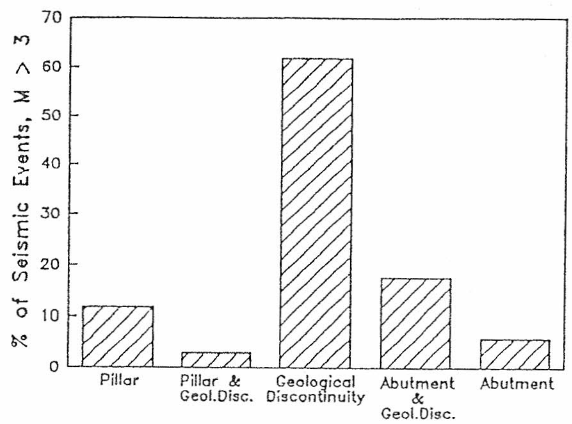

Fig.7 Large seismic events (M>3) and where they occur.

Seismic observations have shown that faults of minor throws (< 10 m) are also able to release events of larger magnitudes (M>3) but never exceeded a magnitude 4,2 on WDL so far.

The following paragraphs document some larger events and try to explain their mechanism. In this context it is noteworthy to state, that more than 90 % of large seismic events on WDL did not cause aftershocks nor were they preceeded by a foreshock of M > 0.

3.1.1. Fault slip

The classical type of seismic event constitutes slip along a plane of weakness (fault or dyke contact). Although the estimation of when and where will movement to a certain extent occur seems to be practical - major problems counteract the prediction of instability in this very simple situation. Limitations and benefits arising from the application of the concept of the excess shear stress ("ESS"), which mainly describes the relationship between the prevailing shear stress and the dynamic properties of the fault plane, were recognized already at its introduction (Ryder, 1988) and later when a number of case studies were carried out (Henderson, 1988, Holmes & Reeson, 1990, Webber, 1990). Main reasons for the limited application of the concept were the extreme sensitivity of ESS calculations on small changes (less than 20 per cent) in

1) the ratio of horizontal to vertical stresses ('k-ratio', normally assumed to be 0.5) and
2) the angle of internal friction.

Deviations from the planar geometry of a fault plane are creating additional problems - suddenly asperities (areas of 'higher friction') occur at places where excess shear stresses would be negative if the undulation of the fault plane is not accounted for. Indirect proof of the ESS concept was found during a monitoring exercise involving the 'Brand' fault in Welkom (Van Aswegen, 1990). The fault plane was modelled extensively taking all available survey data into account. Stress calculations along this surface revealed an area of positive ESS (which was associated with a seismic event M>1 but small displacement - which indicates a high stress drop). The distinction between seismic and aseismic deformation ('creep') is substantial in this context. At this stage emphasis is paid towards the detection of asperities (Mendecki, 1991) which exist along fault planes to delineate areas of potential seismic activity.

3.1.2. Slip along dyke contact

Dykes are the most common geological feature on WDL. Since the beginning of mining operations at WDL some dykes were recognized as potential hazards which has led to the idea that some dykes are rockburst-prone and some are not. Seismicity associated with dykes was found at WDL mainly of a shear-slip nature. Not a single dyke that was mined during the past five years on WDL, remained 'aseismic'. Mining through these features was always accompanied by an increase in the number of seismic events and led to exceptional large events (M>2,8) which do not otherwise occur near a stope face except in the presence of a fault.

Quite often, a dyke is accompanied by dyke-parallel faulting or joints (Pollard & Segall, 1987). This increase in faulting or jointing tends to occur in the ultimate vicinity

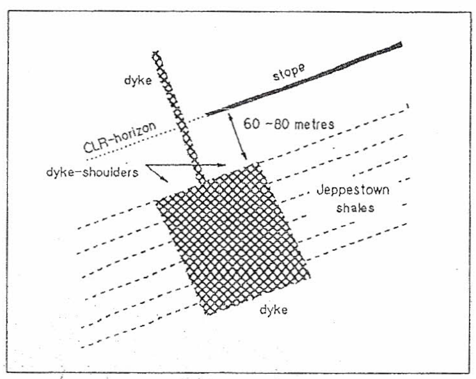

Fig.8 Bulging of Bushveld intrusive dykes.

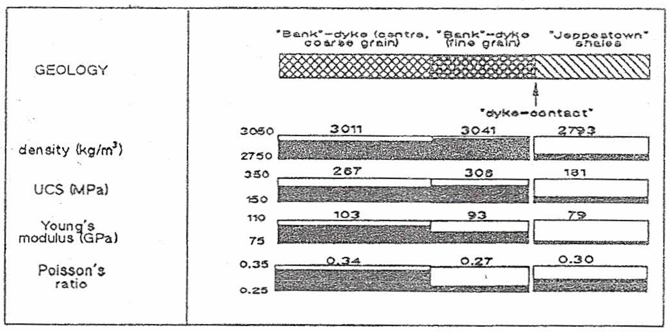

Fig.9 Rock properties near a dyke contact.

of the dyke - between 5 and 10 metres from the dyke contact. This is the area, where small rockbursts ('facebursts') become more and more pronounced. Once the dyke contact is sufficiently exposed (e.g. 50 metres) larger events ('slip along the dyke contact') take place.

However, some dykes behave different. Bushveld intrusives tend to bulge out in the footwall. By the time mining operations reach the dyke-contact on reef - a large portion of the 'dyke-shoulder' in the footwall has been effectively overstoped (Fig.8, Lenhardt, 1992, after Adam, 1990). So far a number of events were observed along the southside of the 'Peggy' dyke-contact deep in the footwall 60 metres before the actual dyke contact on the reef horizon was reached, indicating the extend of bulging of the dyke between 60 metres below the reef. A lateral extent of the 'shoulder' of some of the Bushveld intrusives was confirmed by boreholes when 10-20 m wide dykes reached a width of 100 m in the footwall.

The classical case of a rockburst, during which the stope face is ejected and a seismic event of small magnitude (e.g. M=1) is released, still prevails inside the dyke as many dykes have been found to be inhomogeneous and jointed on WDL. Rock properties within a dyke differ from each other, depending on whether the chilled zone of the dyke (fine grain) or the centre of a dyke (coarse grain) is examined (Fig.9, Lenhardt, 1992).

These properties reflect only the general composition of the dyke, however, and not its strength, which is determined by the inhomogeneities of another nature: joint sets within dykes can be excessive and can cause unstable situations identical with 'facebursts' which are discussed later.

3.1.3 Abutment failure

Sidewalls of longwalls ('abutments') represent areas of stress concentration and are therefore prone to seismic activity at greater depth. In 1986 acoustic emissions were observed (Brink, 1990) before and after a M=3 event occurred near an abutment approximately 2800 metres below surface. After ten events (M>2,8) of this nature (July 1987 and July 1989) some common features became apparent (Lenhardt, 1990):

1) First motions indicated footwall lift in the old mined out area.
2) Events occurred deep in the footwall (60 - 100 metres below reef) along the abutment between 60 and 100 metres ahead of the new approaching long-wall (which changes the mining geometry from an 'abutment' to a 'pillar').
3) Abutment failures tend to occur in the proximity of dykes or faults.
4) The age of the abutment had no bearing on its seismic activity. (Age refers to the time span between the creation of the abutment and its failure).

The mechanism that could explain the 'abutment-failure' involves two stages (Fig.10). During the first stage stress weakening might create unfavourable conditions. Extension fractures near the edge of the excavation continue as shear fractures into the rock mass thus creating a large plane of weakness. At a later stage (Stage 2) the stress tensor rotates when the new longwall approaches and shear slip is initiated. A fault or a dyke intersecting the abutment can facilitate the strain release as it constitutes a potential plane of weakness. Only recently (1st January, 1991) slip along a dyke contact was initiated at WDL by an approaching longwall deep in the footwall (100 metres below reef) at the position where the dyke intersected an abutment.

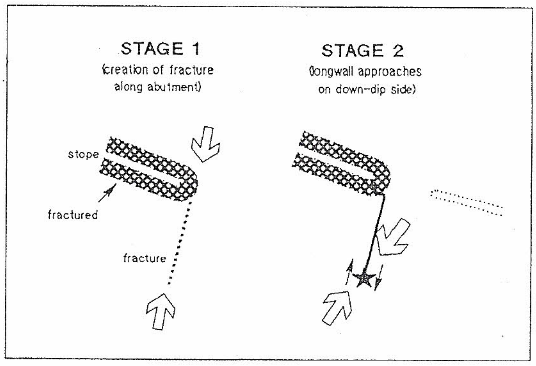

Fig.10 Proposed mechanism of an abutment failure.

3.1.4. Mine-dump

Seismic activity near the surface is most seldom at WDL and was observed on WDL on four occasions between 1986 and 1990.

The first event (M=3.1) located at the edge of mine dump B (not visible in Fig.11). No evidence of recent ground movement was visible on surface and two scenarios were discussed. One explanation was the collapse of a sinkhole beneath the mine dump - because no surface damage could be observed and the event located near the sediment/dolomite discontinuity. The other scenario considered slip along a plane of weakness.

The second event (M=3.5) was located south of mine dump A at a depth of approx. 500 metres and little attention was paid to it. It did not cause any damage and the location was regarded as doubtful. Only at a later time this particular event attracted interest again.

When the third event happened (M=2.8), a first motion study of the geophones was possible. The z-component of each underground geophone was evaluated (Fig. 11, insert) and it was found that half of them showed compressional onsets and the other half of the geophones dilatational onsets. Both types of onsets could be separated by two orthogonal planes. This pattern of 'first motions' is only possible if slip along a fault or a dyke contact takes place - obviously some sensors east of the discontinuity moved upwards and some sensors in the west moved downwards. After the fourth event (M=3.8) surface plans with superimposed geology were collected and data regarding the mine dump retrieved. It became apparent that

Table I Seismic events near the surface

	day	date	time	Mag	depth b.s. in m	comment
1	Fri	870327	7h31	3.1	267	mine dump B
2	Tue	870609	16h16	3.5	336	south of mine dump A
3	Sun	880703	15h25	2.8	125	mine dump A
4	Wed	900110	1h45	3.8	225	mine dump A

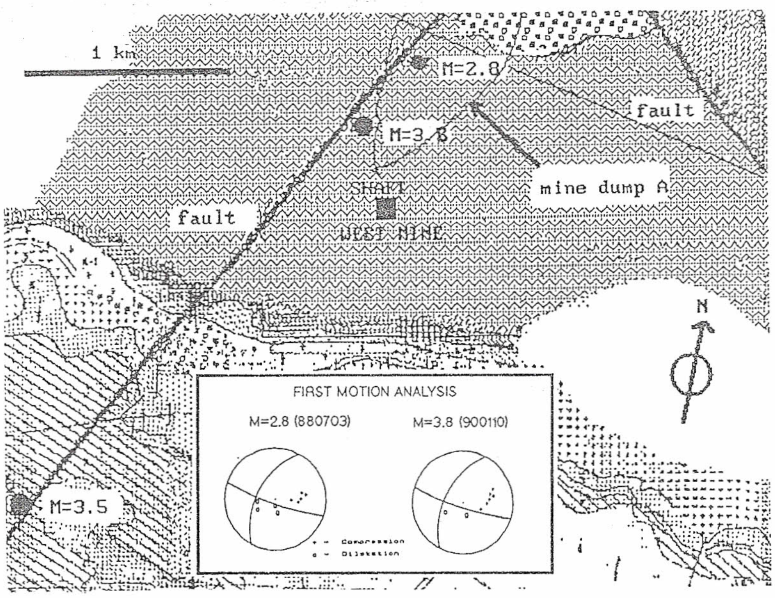

Fig.11 Plan view of the surface geology of WDL Ltd.
(The insert shows two focal solutions)

a considerable mass transfer took place involving mine dump A. It is however impossible to put an accurate figure to the 'critical weight' of mine dumps as this figure depends on the following variables:

a) Geometry and weight of the mine dump.
b) Distance from fault or dyke.
c) Failure characteristics of the fault or dyke.

It can be seen from Table I, that the seismic activity underneath mine dump 'A' was much more pronounced when compared with 'B'. From surface geology plans it became evident that a fault cut across the base of mine dump 'A'. Furthermore, throughout the years, rock was retrieved from one side of the dump (the dumps weight decreased on the east-side) and a new mine dump became established to the west of the fault. The annual 'mass transfer' from the east-side to the west-side amounted to approx. 2 million tons of rock.

All three events near the surface, either directly under or south of mine dump 'A', were found to delineate the fault which cuts across the mine dump. Therefore it seems likely that the mine dump and its mass distribution aggravated the seismic activity along the fault as ratios between mass transfers and released seismic energies were not comparable. Other factors such as the stress regime near the surface could have an influence on the occasional seismicity of this geological feature. The fact that the first motion analysis revealed a strike-slip mechanism indicates, that the intermediate principal stress is oriented vertical (Jaeger & Cook, 1969). The horizontal stress is therefore azimuth-dependent since the larger horizontal stress must - and the smallest horizontal stress must not - exceed the induced stress brought about by the mine dump.

3.2. Non shear-slip events ?

The question arises whether a non-shear slip event can exist at all. On several occasions, even though their frequency is low, seismic events were observed, which could not be explained by a double or single couple of forces. Sometimes all first motions of the geophones were dilatational which indicate an 'implosive mechanism' (Wong & McGarr, 1990). At other occasions both types of first motions were observed - compressional and dilatational ones. But they could not be separated by a set of orthogonal fault planes when conducting a first motion analysis. Both cases indicate an activation of more than one plane of weakness on a small ('implosive', associated with a small magnitude) or large scale (compressional and dilatational first motions - but cannot be separated by orthogonal planes, associated with a large magnitude).

3.2.1. Pillar foundation failure

Stabilizing pillars were introduced at WDL in 1980 to reduce stresses at the stope face and to limit the closure in the back areas. In the beginning, 20 metre pillars at an 85 per cent extraction ratio were left behind for this purpose. Extensive fracturing was observed along the up-dip side of these pillars, which was combated in 1985 by changing the pillar layout to 40 metre pillars. As the extraction ratio remained the same (85 per cent), the span between these pillars had to be doubled. At the same time, the location accuracy of the seismic system at WDL was considerable improved by changing from automatic to manual locations, which allowed to consider the geophone performance, thus avoiding wrong interpretations of the seismic signals. Since then, the seismic activity at the mine can be used to gauge the effectiveness of different mining layouts and support strategies. Monitoring the behaviour of stabilizing pillars became one of the main tasks, and remains high on the priority list of the mine's research team.

Numerous investigations were carried out (Ozbay & Ryder, 1989, Hagan, 1990, Napier, 1990) to validate the efficiency of these regional support units and to focus on their seismic potential.

A research study by Lenhardt (1989b) revealed some typical features related to foundation failures. It was established that large seismic events along pillars are much less dependent on blasting time than their, mainly geology-related, counterparts (Fig.12). Another result indicated that the main deformation process along pillars takes place some distance (about 100 metres) back from the stope face along the edge of the pillar and recurs once a certain longwall advance was accomplished (Lenhardt & Hagan, 1990). Further, the width of pillars (between 20 and 60 metres) was found to have no bearing on the seismic event magnitude (Jantzon et al., 1990). This result indicated that the common design criterion of pillars - the 'average pillar stress' - is inadequate. Instead, shear stresses along the pillar's edge should be considered for pillar design and numerous case studies should be carried out to establish a guideline for pillar design in deep mining.

Acoustic emissions observed from a foundation failure showed clearly that the seismic activity concentrated along the edge of the pillar while the core of the pillar remained more or less unaffected (Lenhardt & Hagan, 1990). This observation explains why the event-magnitude does not correlate with the width of pillars as the determining factor is the extent of failure along the edge of the pillar (which is independent of the width, the mechanism leaves the

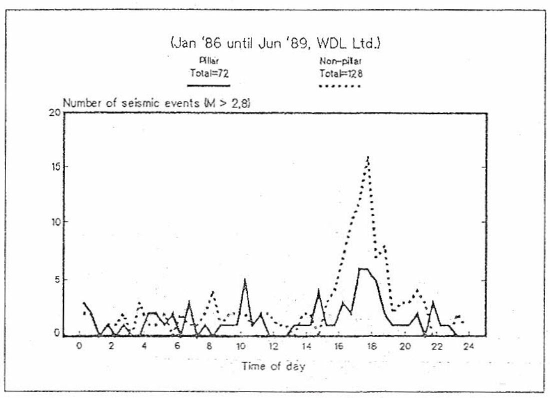

Fig.12 Diurnal distribution of large events (M>2,8).

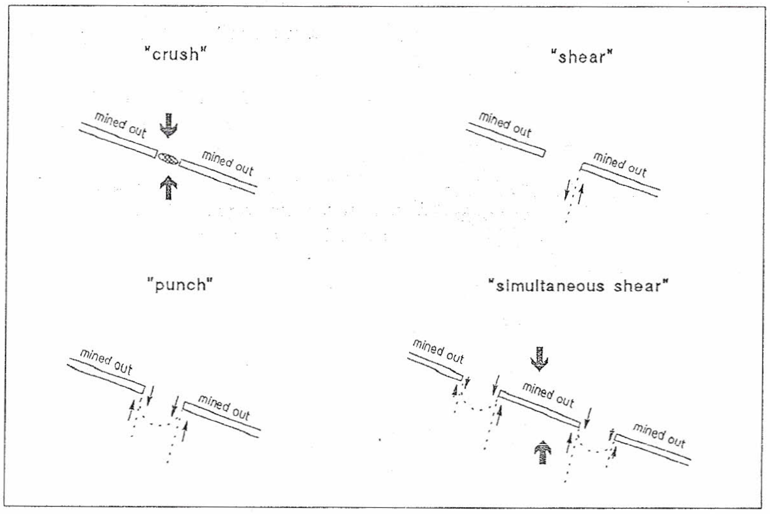

Fig.13 Proposed mechanisms of 'pillar'-failures.

pillar-core intact), and not across the pillar (dependent of the width, mechanism: crush-type).

Some foundation failures could be interpreted definitely as 'shear-slip' events - others could not (shear-slip events were observed along pillars which were left along geological discontinuities, e.g. 'Wuddles dyke' on the VCR). Finally, based on all the seismic and underground observations, several models of pillar failures were postulated (Fig. 13, Lenhardt & Hagan, 1990).

The effect of footwall geology was recognized to be of outmost importance when the performance of pillars on the shallower VCR horizon were evaluated (Leach & Lenhardt, 1990). Two mining sections at the same depth (approx. 2200 metres below surface) were subjected to completely different seismic patterns. One section was affected 16 times by foundation failures (M>2,8) while the other section experienced only one event of large magnitude during the same period of time (Jan '86 until June '89). The reason for this discrepancy was found in the foundation rocks of the reef. Areas where quartzitic rock forms the immediate footwall of the reef were exposed to highest seismicity levels along pillars. The other mining section is underlain by shales, which tend to deform plasticly - hence do not permit shear stresses to build up until they reach critical levels.

3.2.2 Crush

The intrinsic failure of a pillar has not been observed on WDL with the seismic network. But seismic events of moderate magnitudes (M=1-2) were sometimes observed which indicated an 'implosive' mechanism. The damage pattern resembles itself in many cases and it is striking that this type of event seems to be very common on the VCR horizon and occurs seldom on the deeper CLR horizon. The name 'faceburst' has been used in the past to describe and distinguish this seismic event from others which are related to different mechanisms (shear failure of the rock mass on a large scale). The following patterns of circumstances which accompany facebursts have been observed so far:

1) facebursts occur mainly on VCR (stoping width slightly higher than on CLR)
2) the control of hangingwall was sometimes lost during previous blasts (increase in joint sets ?)
3) reef roll was sometimes apparent
4) the magnitudeof damaging events averaged M=1.1
5) the theoretical energy release rate is very low (ERR < 10 MJ/m^2)

A search for the causes of these facebursts gained momentum after these common factors had been detected. As a working hypothesis the following two scenarios were adopted:

Scenario A
1) Reef roll provokes drilling into the hangingwall.
2) A fall of ground occurs during blast leaving the brow behind.
3) An undercut is attempted to restore the stoping width.
4) The stresses at stope face are altered by the presence of the brow.
5) A faceburst occurs due to excess shear stresses at the stope face (facilitated by the presence of joint sets and an increase of shear stresses ahead of the stope face due to the presence of the brow).

Scenario B
1) The density of the joint sets increases (e.g. while approaching a dyke).
2) The stope moves from stable ground (joint spacing large) to unstable ground (joint spacing small).
3) A faceburst occurs due to the reduced strength of stope face.

4. Practical implications and conclusions

The classification of rockbursts assists in adopting proper counter-measures. Several categories of seismic events that lead to rockbursts have been identified according to their striking resemblance in terms of damage, seismicity, and existing mining configurations. It is hoped that the chart shown in Figure 14 can be of assistance when seismic problems occur in a mining environment for which only sparse seismic information is available. Once the cause of an event has been established, efforts can be concentrated towards the prevention of control of its effects. Mine-dump events have been excluded from Figure 14 and will not be discussed in this paragraph as they do not cause damage to underground workings.

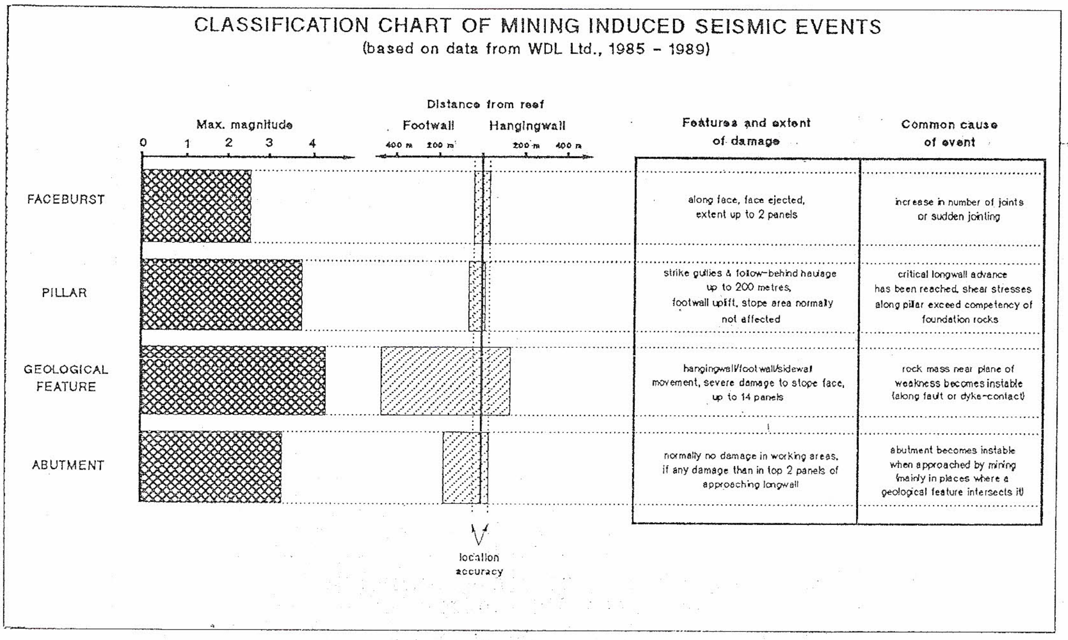

Fig.14 Categories of deep-mining-induced seismic events.
(based on data from WDL Ltd., 1985-1989)

The kind of seismic event that is created by slip along a plane of weakness ('fault-slip' or 'slip along a dyke contact', can be 'controlled' by two means:

1) stabilizing the feature (e.g. mining geometry), or
2) de-stabilizing the feature (e.g. triggering blasts).

The first method involves proper orientation of the longwall shape when negotiating a geological feature. Bracketing the feature creates artificial asperities along the fault or dyke-contact which help to stabilize the rockmass. Bracket pillars will certainly become seismically active, but at a later stage after mining has been completed in the feature's vicinity. 'Triggering' is the most critical method since very little is known about the potential of initiated fault slip. Also a balance must be found between the size, type and pattern of the charge and damage due to manmade fracturing of the rock mass that might call for additional support.

Stope support can only assist in minimizing the damage (by reducing the extent of falls of ground), but cannot prevent the seismic event from happening. Backfill, for example, has been found to be not effective in controlling geological features (Fig.15). In practice most panels, which advance through geological features, are not backfilled because the provision of sufficient hangingwall control by area support (packs) becomes imperative (Henderson, 1991).

Although backfill does not seem to contribute towards the stability of excavations near faults or dykes, its potential in combating the foundation failure problem of stabilizing pillars is very high indeed. Backfill becomes more and more effective with increasing compression - which is the case in the back area, especially on the deeper horizon (Carbon Leader reef). Backfill is expected to reduce the load on pillars thus preventing the edges of the pillar to exceed the critical shear stress that would ultimately lead to a foundation failure.

Abutment-failures are not likely to be controllable, since the source region extends very deep into the footwall and trigger-blasts become unpractical. Moreover, the mining geometry cannot be changed to prevent this type of event from happening. The only remedy is to accept that such an event is possible, and to avoid placing footwall developments near the intersection of an abutment and a dyke or a fault. As this region is weakened by the presence of the geological feature, it is likely to fail when approached by a longwall.

The most effective countermeasure for crush-type events, which affect small areas, could be de-stressing blasts. This method is critical and demands the same

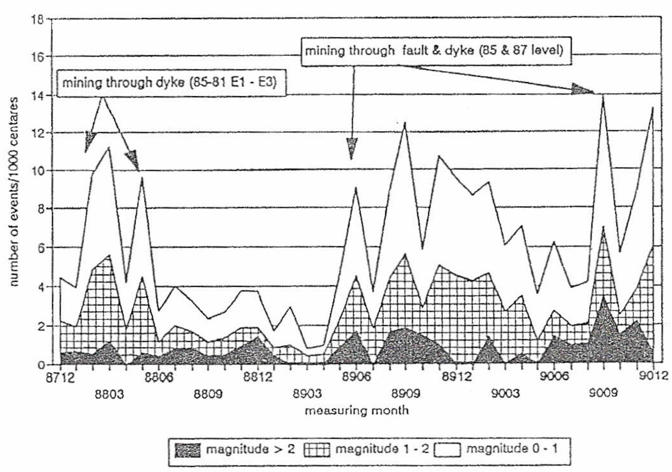

Fig.15 Seismicity of a backfilled mini-longwall.

attention as 'trigger-blasts'. Most encouraging would be a specialized blasting method which can be incorporated into the production blast pattern.

Seismic data can be used to monitor stress changes brought forward by mining, thus indicating the rockmass properties. By evaluating this information the rock engineering practitioner gains an insight into the genuine local rockmass behaviour and can take appropriate action, such as intensified local support that minimizes the extent of falls of ground associated with seismic activity. When modelling is carried out, the time dependent deformation of the rockmass should be taken into account.

Monitoring of the rockmass with all available means solves debatable questions as to whether regional support strategies satisfy our expectancies. Seismic networks can assist here as a monitoring unit on a large scale to delineate critical areas where additional steps need to be taken to ensure safe mining operations.

REFERENCES

Adam, T (1990). Unpublished internal geology report. Anglo American Corporation, Western Deep Levels East mine, South Africa.

Brink, A v Z (1990). Application of a microseismic system at Western Deep Levels.Proc. of 2nd Symposium 'Rockburst and Seismicity in Mines', Fairhurst (ed.), Balkema, pp. 355-362.

Hagan, T O (1990). Pillar foundation studies at a deep South African gold mine. Proc. of 2nd Symposium 'Rockburst and Seismicity in Mines', Fairhurst (ed.), Balkema, pp. 65-70.

Hanks, T C & Kanamori, H (1979). A moment magnitude scale, J. Geoph. Res.84, pp. 2348-2350.

Henderson, N B (1988). Back analysis using the excess shear stress criterion on longwall mining strategies. Proc. of '1st Regional Conference for Africa - Rock Mechanics in Africa', Swaziland, SANGORM, pp. 35-40.

Henderson, N B (1991): Personal communication.

Holmes, R D & Reeson, J A (1990). Excess shear stress (ESS) - A case study. Proc. of 2nd Symposium 'Rockbursts and Seismicity in Mines', Fairhurst (ed.), Balkema, pp. 331-336.

Jaeger, J C & Cook, N G W (1969). Fundamentals of Rock Mechanics. Chapman & Hall.

Jantzon, F G H, Hagan, T O & Lenhardt, W A (1990). An evaluation of regional support strategies at Western Deep Levels Limited. 'International Deep Mining Conference', Johannesburg, South Africa, SAIMM, Symposium Series S10, pp.1195-1199.

Leach, A R & Lenhardt, W A (1990). Pillar associated seismicity on Western Deep Levels South mine. 'Static and dynamic considerations in Rock Engineering', Proc. of 2nd Regional Conference for Africa Conference, Brummer (ed.), Balkema, pp. 197-205.

Lenhardt, W A (1988). Some observations regarding the influence of geology on mining induced seismicity at Western Deep Levels Limited. Proc. of '1st Regional Conference for Africa - Rock Mechanics in Africa', Swaziland, SANGORM, pp. 45-48.

Lenhardt, W A (1989a). Seismic event characteristics in a deep level mining environment. Symposium 'Rock at great depth', Maury & Fourmaintraux (eds.), Balkema, pp. 727-732.

Lenhardt, W A (1989b). Stabilizing pillars. Internal Research Study, Anglo American Corporation, Regional Rock Mechanics Department, Western Deep Levels Limited.

Lenhardt, W A (1990). Seismic events associated with large mining induced fractures. Proc. of conference 'Mechanics of jointed and faulted rock', Rossmanith (ed.), Balkema, pp. 727-731.

Lenhardt, W A (1992). Seismicity associated with deep-level mining at Western Deep Levels Limited. J.S.Afr.Inst.Min.Metall., vol.92, no.5, pp.113-120.

Lenhardt, W A & Hagan, T O (1990). Observations and possible mechanisms of pillar associated seismicity at great depth. 'International Deep Mining Conference', Johannesburg, South Africa, SAIMM, Symposium Series S10, pp. 1183-1194.

McGarr, A (1984). Scaling of ground motion parameters, state of stress, and focal depth, J. Geophys. Res. 89, pp. 6969-6979.

Mendecki, A J, Van Aswegen, G, Brown, J N R & Hewlett, P (1990). The Welkom Seismological Network, Proc. of 2nd Symposium 'Rockbursts and Seismicity in Mines', Fairhurst (ed.), Balkema, pp. 234-244.

Mendecki, A J (1991): Personal communication.

Napier, J A L (1990). Modelling of fracturing near deep level gold mine excavations using a displacement discontinuity approach. Proc. of conference 'Mechanics of jointed and faulted rock', Rossmanith (ed.), Balkema, pp. 709-715.

Ortlepp, W D (1984). Rockbursts in South African gold mines: A phenomenological view. Proc. 1st Conf. "Rockbursts and Seismicity in Mines", Gay & Wainwright (eds.), Johannesburg, South African Inst. of Mining and Metallurgy, Series 6, pp. 165-178.

Ozbay, M U & Ryder, J A (1989). Investigations into foundation failure mechanisms of hard rock squat rib pillars. Symposium 'Rock at great depth', Maury & Fourmaintraux (eds.), Balkema, pp. 527-735.

Piterek, A & Lenhardt, W A (1990). Blasting induced seismicity in an ultra deep level mine. 'Static and dynamic considerations in Rock Engineering', Proc. of 2nd Regional Conference for Africa Conference, Brummer (ed.), Balkema, pp. 251 - 256.

Pollard, D D & Segall, P (1987). Theoretical displacements and stresses near fractures in rock: with applications to faults, joints, veins, dykes and solution surfaces, in 'Fracture Mechanics of Rock', Atkinson, B K (ed.), Academic Press geology series, pp. 277-349.

Ryder, J A (1988). Excess shear stress in the assessment of geologically hazardous situations. J.S.Afr.Inst.Min.Metall., 88, pp. 27-39.

Spottiswoode, S M (1989). Perspectives on seismic and rockburst research in the South African gold mining industry: 1983 - 1987. in 'Seismicity in Mines', Gibowicz (ed.), Birkhäuser Verlag, pp. 673-680.

Van Aswegen, G (1990). Fault stability in SA gold mines. Proc. of Conference 'Mechanics of jointed and faulted rock', Rossmanith (ed.), Balkema, pp. 717-725.

Webber, S J (1990). Quantitative modelling of mining induced seismicity. Unpubl. MSc thesis, Univ. of the Witwatersrand, Johannesburg, South Africa.

Wong, I G & McGarr, A (1990). Implosional failure in mining-induced seismicity. Proc. 2nd Symposium 'Rockbursts and Seismicity in Mines', Fairhurst (ed.), Balkema, pp. 45-52.